

**IGNITION OF
HYDROGEN-FLUORINATED OXIDIZERS
FINAL REPORT**

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FOREWORD

This report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation under Contract NAS3-7964. The contract was administered by the National Aeronautics and Space Administration, Lewis Research Center, Chemical and Nuclear Rocket Procurement Section, Cleveland, Ohio. The NASA Project Manager for the contract was Mr. E. A. Edelman. This is the final report on the contract, summarizing technical effort during the period 30 June to 30 November 1966.

The following personnel at the Pratt & Whitney Aircraft Florida Research and Development Center contributed to the technical effort and preparation of this report: W. J. McAnally, J. M. Bryant, P. A. Thomas, and S. A. Mosier.

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SECTION I
INTRODUCTION

The high-energy propellant combination, oxygen and hydrogen, has the potential of high specific impulse for upper-stage rocket propulsion systems. However, the propellants do not ignite spontaneously and therefore some means must be provided for initiating combustion. Various methods of igniting oxygen/hydrogen rocket engines include electric spark systems, hot and exploding wires, injection of a hypergolic third propellant at start, and use of ignition-initiating additives in one propellant to make the combination hypergolic.

The electric spark igniter has been developed to a high degree of reliability, as in the Pratt & Whitney RL10 oxygen/hydrogen rocket engine. However, in the interests of simplification it would be desirable to eliminate separate ignition systems; in addition, minor weight savings would be realized. Hot-wire ignition systems have the same basic disadvantages as electric spark systems, as do exploding wire systems, which also are generally limited to a single operational cycle. Injection of a third propellant, such as triethylborane, into the combustion chamber in conjunction with an oxidizer lead is very effective but this approach requires another complete propellant supply system for more than one start.

Although the use of ignition-initiating additives has not been applied to a great degree, this technique offers considerable potential as a reliable means for effecting hypergolic ignition of oxygen and hydrogen. The use of small percentages of ozone fluoride (O_3F_2) in liquid oxygen has been shown to be effective for igniting O_2/H_2 rocket engines, but there is a problem of additive stability. The use of fluorine as an additive to liquid oxygen to initiate combustion has been suggested, and the idea is appealing if large amounts of fluorine are not required. However, the minimum fluorine concentration necessary to assure ignition has not been well defined.

If the amount of fluorine in the oxidizer required for reliable hypergolic ignition is low (10% or less) material compatibility problems involved in application of the technique are minimized, and the conversion of existing vehicle and engine oxidizer systems would not be difficult. The effect on launch operations would be limited, and the approach could also be used for future vehicles. Guaranteed ignition and multiple restart capability would facilitate use of oxygen/hydrogen in attitude control systems, which then could use the same propellants as the main engine, vastly simplifying vehicles that now must employ different propellants and a separate supply system for this function.

However, if a large percentage of fluorine is required, the entire vehicle and engine oxidizer system would have to be designed essentially for 100% fluorine service. If this were done, it would be more appropriate to use 100% fluorine to take advantage of the greater specific impulse potential that is available using fluorine/hydrogen instead of oxygen/hydrogen.

It is therefore important that the hypergolic ignition limits for hydrogen and fluorine-oxygen mixtures be established at conditions likely to be encountered in space engines at ignition. Tests in laboratory-type apparatus do not provide adequate definition. Ignition test hardware must be functionally and geometrically representative of a flowing combustor, similar to the engine system in which the propellant combination might ultimately be used, if representative data are to be obtained. Although the data resulting from a small-scale replica of a rocket engine are relative (rather than absolute), a much closer approximation to the ignition delay characteristics associated with the propellant mixing and turbulence in a full-size combustion chamber can be obtained.

The experimental program described herein was undertaken to determine the minimum percentage fluorine in oxygen necessary to achieve repeatable hypergolic ignition with hydrogen under simulated upper-stage liquid rocket operating conditions. The program was accomplished by conducting a series of tests over a range of flox/hydrogen mixture ratios with flox containing various percentages of fluorine. The small-scale rocket motor used and the propellants were maintained at liquid nitrogen temperatures. Special high-frequency response instrumentation was used to

sense ignition. The necessary close control of all test operating conditions and the rapid recording and reduction of test data were possible through use of an electronic events sequencing system and a digital data acquisition system existing at the test facility.

SECTION II
SUMMARY

The program objective, experimental definition of the limits of hypergolicity of fluorine-oxygen mixtures with hydrogen under liquid rocket operating conditions, was accomplished by conducting five series of ignition tests. For each series, a different percentage of fluorine in the flox mixture was used, and tests were conducted at mixture ratios of approximately 1, 5 and 8. High-frequency response instrumentation was used to sense ignition of cold gaseous hydrogen with pure fluorine and flox mixtures containing 53.4, 50.2, 46.5 and 39.5% fluorine under altitude conditions in a small-scale rocket engine which was liquid nitrogen cooled.

Rapid ignition with minimum variation in delay times was demonstrated with pure fluorine. No ignition was recorded for the tests conducted with 39.5% fluorine in flox, whereas in the tests conducted with concentrations of 46.5, 50.2 and 53.4% fluorine in flox, ignition and/or sustained combustion was not obtained under all conditions. These results indicate that for practical design purposes the flox concentration necessary for consistent ignition is sufficiently high to require that vehicle and engine systems using the mixture must be compatible with pure fluorine.

SECTION III CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the experimental results obtained in the flox/hydrogen ignition program, it is concluded that:

1. Greater than 53.4% fluorine in flox mixtures is required to achieve reliable hypergolic ignition under altitude liquid rocket operating conditions using type 347 stainless steel injector and chamber hardware.
2. To a minor degree, increasing the mixture ratio decreased ignition delay times and increased the probability of combustion being sustained after ignition had occurred.
3. Starting at atmospheric chamber pressure decreased the probability that ignition would occur.

B. RECOMMENDATIONS

Because of the number of conditions that influence ignition, it is possible that the percentage of fluorine in flox required for reliable hypergolic ignition, as determined from this investigation, can be significantly reduced. It is therefore recommended that additional experimental testing be conducted to determine the effect of:

1. Maintaining injection momentum ratio constant while increasing mixture ratio.
2. Increasing propellant mixing through variations in injector design.
3. Providing a definite precedence for one of the propellants during the start transient.
4. Providing trace amounts of organic substances in the hydrogen.
5. Increasing one or both propellant temperatures.
6. Using different chamber wall materials.

With respect to the last item, it is known that important reactions take place at the metallic walls of a combustion chamber and that different metals produce different results. Recent German experiments described in the Third Reynolds-Prandtl Lecture (Reference 1) indicate that copper has a strong catalytic effect in the fluorine/hydrogen reaction.

SECTION IV
IGNITION TEST PROGRAM

A. IGNITION TEST RIG

The ignition test rig used in the investigation is shown schematically in figure 1. It consists of three parts: a single-element impinging jet injector; a combustion chamber having the geometry of a small-scale rocket motor; and an exhaust plenum for use in altitude simulation. The injector and chamber were available from a flox/light hydrocarbon hypergolicity program described in Reference 2.

The small-scale rocket chamber is constructed of type 347 stainless steel, and is 1.2 inches in diameter over a 2.6-inch length from the injector face to a convergent section upstream of the chamber throat. The convergent and divergent sections of the integral expansion nozzle are at angles of 45 and 30 degrees to the chamber axis respectively. With the throat diameter of 0.4 inch, the characteristic chamber length is approximately 25 inches. A liquid nitrogen cooling jacket is provided to maintain the chamber body at liquid nitrogen temperatures. Steps were taken to assure good cooling at the throat and to minimize thermal conduction from the uncooled exhaust plenum flange. A thermocouple was installed in the vicinity of the throat to monitor chamber body temperature.

The single element, triplet-type impinging jet (three fuel on one oxidizer) injector used in the investigation is shown in figure 2. The oxidizer flow area is 0.00204 in.^2 and the total flow area of the three fuel orifices is 0.0182 in.^2 . The fuel impingement angle is 60 degrees with respect to the injector face and impingement occurs approximately 0.312 in. from the injector surface. The type 347 stainless steel injector body was fabricated with an integral liquid nitrogen cooling passage to prevent heating of the liquified flox and cold, gaseous hydrogen during start transients. A thermocouple was provided to monitor injector body temperature.

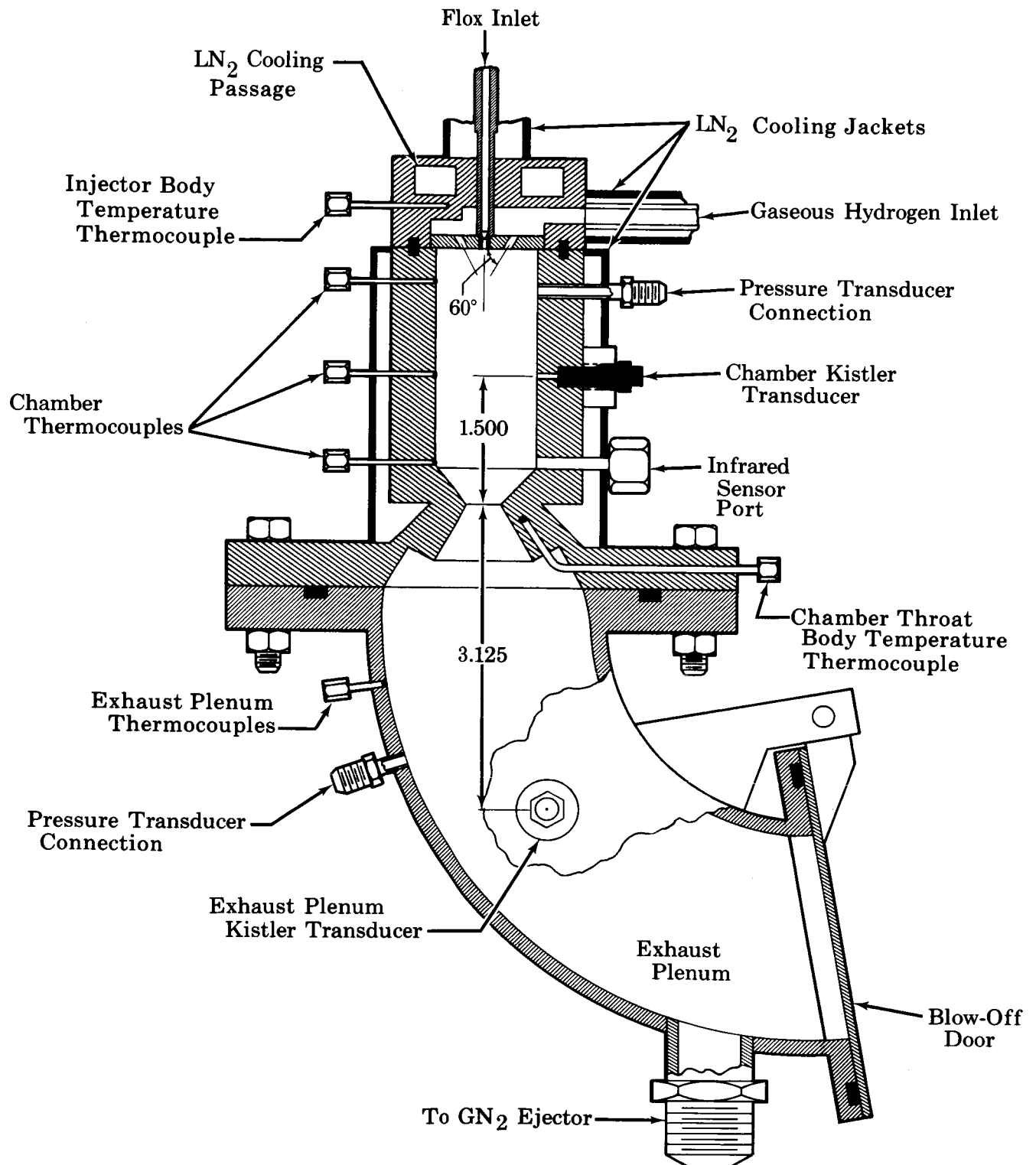


Figure 1. Ignition Test Rig Schematic

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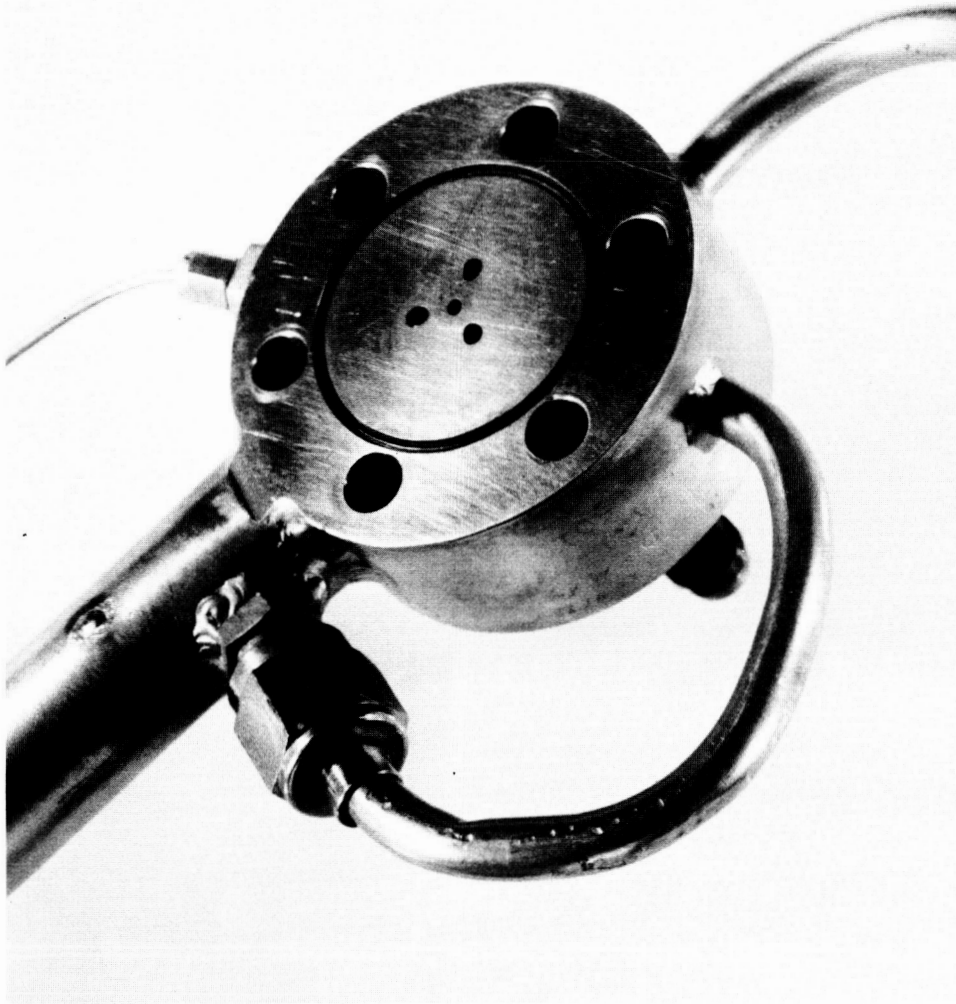


Figure 2. Triplet-Type Impinging Jet Injector

FE 64991

The reduced-pressure exhaust plenum was utilized to simulate altitude conditions, minimize residual purge gas in the chamber prior to initiation of oxidizer and fuel flow, and to prevent frost formation on the cooled internal injector and chamber surfaces. The exhaust plenum was evacuated with a gaseous nitrogen operated ejector to provide approximately a 1-psia ambient pressure environment in the combustion chamber. A hinged blow-off door, held in place by the differential pressure generated by the ejector, provided closure prior to ignition. At ignition, the pressure generated within the chamber caused the door to open. The exhaust chamber was not liquid-nitrogen cooled. It was believed that frost formation in the vicinity of the blow-off door would have interfered with opening, thereby causing operational delays.

B. TEST FACILITY AND INSTRUMENTATION

The hypergolic ignition investigation was accomplished in the B-7 test stand of the Rocket Engine Component Test Area at Pratt & Whitney Aircraft's Florida Research and Development Center. The ignition test apparatus installed in the test stand is shown in figure 3. A detailed description of the test facility, its propellant supply system, digital sequencer and high-speed digital tape recording system, is given in Appendix A. A schematic of the test stand propellant system is presented in figure 4. The solenoid-type run valves shown in figure 4 were special liquid-nitrogen submersible, fluorine compatible valves that had been used in the Reference 2 flox/light hydrocarbon hypergolicity program. These valves feature good repeatability and fast response.

In addition to standard instrumentation for pressure and temperature measurements, special high-frequency response instrumentation was provided to sense ignition. Piezoelectric dynamic pressure transducers (marketed by Kistler Instrument Corporation) and an infrared radiation sensor were used. The infrared sensor was installed in the thrust chamber; Kistler transducers were installed in both the combustion chamber and the exhaust plenum so that the point at which ignition occurred (inside or outside the combustion chamber) could be established. The differential in time between indications from the Kistler transducer in the combustion chamber and that in the exhaust plenum provided the necessary definition.

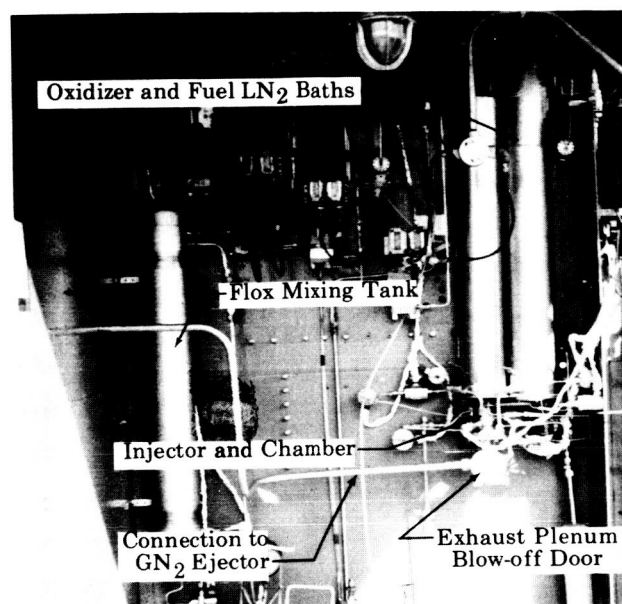


Figure 3. Ignition Test Apparatus on B-7 Stand

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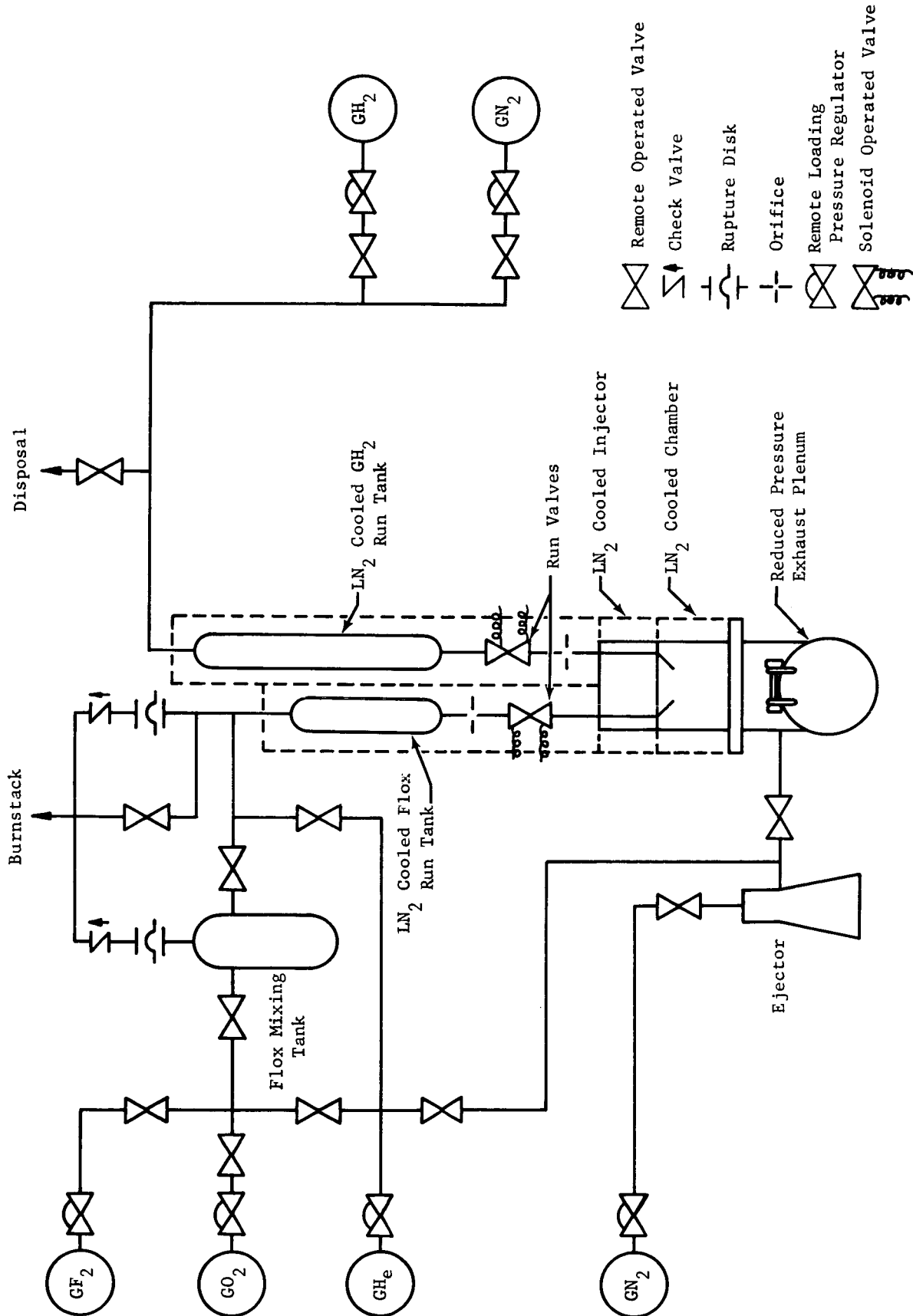


Figure 4. B-7 Stand Propellant System Schematic

FD 19117

Kistler transducers incorporate a natural quartz crystal sensing element with flush diaphragm construction, and they are capable of a 3-microsecond rise time to a step increase in pressure. The infrared radiation sensor is a cadmium selenide photoconduction device that registers ignition as a step change in voltage across the photoconductive cell. The response of the photoconductive cell is 1 millisecond to 63% of the step change in voltage.

C. TEST PROCEDURES

The partial pressure method was used to prepare flox mixtures. Gaseous fluorine and oxygen at 540°R can be considered thermodynamically perfect gases over a wide range of pressures. Since mixtures of the two can likewise be considered to act as perfect gases, the chemical composition of fluorine-oxygen mixtures was calculated from the equation of state, using the partial pressure of each constituent and the volume of the flox mixing tank. The use of Dalton's Law* to determine the partial pressures assured statistically that the total error in flox concentration would be less than $\pm 1\%$. In preparing the computer program used to calculate flox percentages, steps were taken to account for residual amounts of helium purge gas present in the flox mixing tank prior to adding fluorine and oxygen.

To assure high purity, the gaseous fluorine used was obtained by vaporizing liquid fluorine. Table I is the supplier's** analysis of the liquid fluorine shipment (from which the gaseous fluorine was generated).

Table I. Liquid Fluorine Analysis, Weight Percentage Basis

Fluorine	99.8
Hydrofluoric Acid	0.03
Carbon Tetrafluoride	0.02
Oxygen	0.12
Nitrogen	0.03

* The pressure of a mixture of gases is equal to the sum of the partial pressures of the individual components taken each at the temperature and volume of the mixture.

**Allied Chemical Company

Prepared mixtures of gaseous oxygen and fluorine were transferred to the liquid-nitrogen-cooled oxidizer run tank where they were liquified. The liquid flox was pressurized with dry gaseous helium to a level precalculated to produce the desired flow rate. Similarly, the liquid-nitrogen-cooled fuel run tank was pressurized with gaseous hydrogen.

The results of six injector cold flows with liquid nitrogen and cold gaseous hydrogen indicated that the oxidizer and fuel solenoid run valves should be energized simultaneously to achieve as near simultaneous propellant injection as possible. This valve timing was determined by correlating oscillograph analog propellant flow traces with high-speed motion pictures of the injector spray pattern.

Each test was initiated by energizing the electronic digital sequencer controlling the flow of purge gas, ejector operation, propellant flow sequence, test duration and fuel lag at shutdown. The sequence of events for a test was:

1. Initiate ejector operation
2. Terminate fuel and oxidizer injector purges
3. Energize fuel and oxidizer solenoid run valves simultaneously
4. After approximately 700 milliseconds, close oxidizer run valve and open the oxidizer purge valve simultaneously
5. Close fuel run valve and open fuel purge valve simultaneously
6. Terminate ejector operation.

D. TEST RESULTS

Five series of tests were conducted with fluorine-oxygen mixtures containing various percentages of fluorine. The first test series was conducted with pure fluorine to establish base ignition delay times; remaining test series were conducted using concentrations of 53.4, 39.5, 50.2 and 46.5% fluorine in flox. With each oxidizer mixture, tests were conducted at mixture ratios of approximately 1.5 and 8.

A summary of ignition delay times and performance data for all tests is presented in table II. The values listed for mixture ratio, chamber pressure, propellant flow, and injection momentum ratio are averages of 10 scans of microsecond data (82 scans per sec) during relatively steady-state portions of each test.

A typical oscillograph analog trace showing ignition (from test No. 15.01) is presented in figure 5. Because ignition delay time is a relative measurement and is dependent not only on the chemical affinity between the oxidizer and the fuel, but also on the hydrodynamic effects produced by the injector and chamber configuration, ignition delay time was defined as the time increment between energization of the solenoid valves and the occurrence of ignition. The indication of ignition was a sharp rise in the chamber pressure trace from the Kistler transducer. That sensor consistently responded faster than the infrared sensor or the three bare-wire thermocouples in the combustion chamber.

Because of an error in the flow mixing procedure, the flow percentage listed for tests No. 12.01 through 20.01 has been corrected to include a small residual amount of fluorine that was in the oxygen side of the flow mixing system.

The base ignition delay times for the first series of tests, conducted with pure fluorine, ranged from 11.9 to 25.4 millisecond.

Ignition delay times for the second series of tests, using 53.4% fluorine in flow, ranged from 32.3 to 471 millisecond. In one of the tests at a mixture ratio of approximately 1, combustion was not sustained after a 204-millisecond delayed ignition; however, 88 millisecond later ignition occurred again and this time combustion was sustained. During this series of tests no ignition was recorded for two of four tests that were initiated at atmospheric chamber pressure (because of an exhaust plenum blow-off door air leak). When the tests were repeated with the ejector operating properly, the shortest ignition delays of that test series resulted.

Table II. Summary of Flox/Hydrogen Ignition Delay Times and Performance Data

Ignition Test Number	Fluorine in Flox, %	Ignition Delay Time, msec	P. Prior to Start, psia	Steady-State Mixture Ratio	Chamber Pressure, psia	Propellant Flow Rate, lb/sec	Injection Momentum Ratio	Steady-State Equivalence Ratio	Fuel Temperature, °R	Oxidizer Temperature, °R	Injector Temperature, °R	Chamber Temperature, °R	Remarks
2.01	100	11.9	1.05	2.98	108	0.0598	5.15	6.33	137	138	153	151	
3.02	100	25.6	1.07	6.52	86.8	0.0603	1.97	2.89	137	137	153	155	
4.02	100	12.4	1.05	0.890	101	0.0647	22.2	21.2	133	138	157	132	
5.01	100	14.9	1.08	0.790	98.4	0.0611	27.9	23.9	133	137	149	134	
6.01	100	22.0	14.7	6.33	92.0	0.0593	1.77	2.97	136	138	159	160	Exhaust plenum blow-off door leaked.
8.01	100	22.0	1.24	5.59	92.1	0.0581	2.09	3.37	138	138	153	159	
9.01	100	21.5	1.12	5.85	92.8	0.0595	1.69	3.22	138	138	151	160	
10.01	100	18.0	1.09	8.18	87.0	0.0658	1.21	2.30	138	134	156	158	
11.01	100	23.8	1.12	8.71	84.5	0.0667	1.14	2.16	138	134	152	162	
12.01	53.4*	471	1.02	0.800	98.9	0.0609	22.4	14.4	135	139	154	159	Combustion not sustained after first ignition.
13.01	53.4*	204/292	1.15	0.900	105	0.0625	14.8	12.8	134	139	154	158	Exhaust plenum blow-off door damaged.
14.01	53.4*	348	1.07	0.720	89.9	0.0572	29.4	16.0	134	139	156	158	Exhaust plenum blow-off door leaked.
15.01	53.4*	60.5	14.6	5.00	98.2	0.0556	1.34	2.30	137	139	157	160	Exhaust plenum blow-off door leaked.
16.01	53.4*	49.8	14.7	5.04	100	0.0553	1.61	2.28	137	139	156	162	Exhaust plenum blow-off door leaked.
17.01	53.4*	No ign.	14.7	7.65	19.6	0.0734	1.01	1.50	138	139	157	164	Exhaust plenum blow-off door leaked.
18.01	53.4*	No ign.	14.7	7.68	19.3	0.0732	0.999	1.50	139	139	157	164	Exhaust plenum blow-off door leaked.
19.01	53.4*	32.8	1.15	7.60	91.2	0.0645	1.06	1.51	138	139	152	164	Exhaust plenum blow-off door leaked.
20.01	53.4*	48.7	1.07	7.37	81.4	0.0634	0.862	1.36	138	139	150	157	Flox depletion occurred prior to shutdown.
21.01	39.5	No ign.	1.18	1.38	33.3	0.0865	5.03	7.46	134	138	148	156	
22.01	39.5	No ign.	1.16	1.36	32.3	0.0843	5.24	7.57	134	139	150	158	
23.01	39.5	No ign.	1.14	3.08	21.9	0.0705	2.47	3.34	136	138	155	155	
24.01	39.5	No ign.	1.13	3.14	21.7	0.0700	2.46	3.28	137	139	152	159	
25.01	39.5	No ign.	1.13	5.14	19.3	0.0693	1.53	2.00	137	138	149	158	
26.01	39.5	No ign.	1.13	4.82	20.0	0.0649	1.85	2.13	138	137	153	158	
27.01	39.5	No ign.	1.12	6.12	18.0	0.0680	1.37	1.68	139	138	150	159	Flox depletion occurred prior to shutdown.
30.01	50.2	48.2	1.20	0.860	109	0.0660	20.3	13.0	136	140	154	148	
31.01	50.2	179	1.12	0.730	101	0.0644	29.8	15.3	135	140	151	150	Ignited in exhaust plenum first, but combustion not sustained.
32.01	50.2	509	2.25	1.07	30.4	0.0716	9.38	10.5	135	139	152	150	
33.01	50.2	201	1.10	5.40	93.4	0.0550	1.91	2.07	138	139	167	158	Exhaust plenum blow-off door leaked.
34.01	50.2	260	10.8	4.54	104	0.0543	2.34	2.46	138	139	165	164	
35.01	50.2	309	1.06	6.77	82.1	0.0644	1.25	1.65	138	139	158	159	
36.01	50.2	74.7	1.18	8.18	62.4	0.0651	0.992	1.37	139	144	145	—	Flox depletion occurred prior to shutdown.
37.01	46.5	265	1.13	0.830	28.3	0.0702	12.1	13.1	138	139	157	164	Combustion not sustained after ignition. Fluorine reaction in solenoid run valve precluded further testing.

*Correction has been applied to account for an error in Flox mixing procedure.

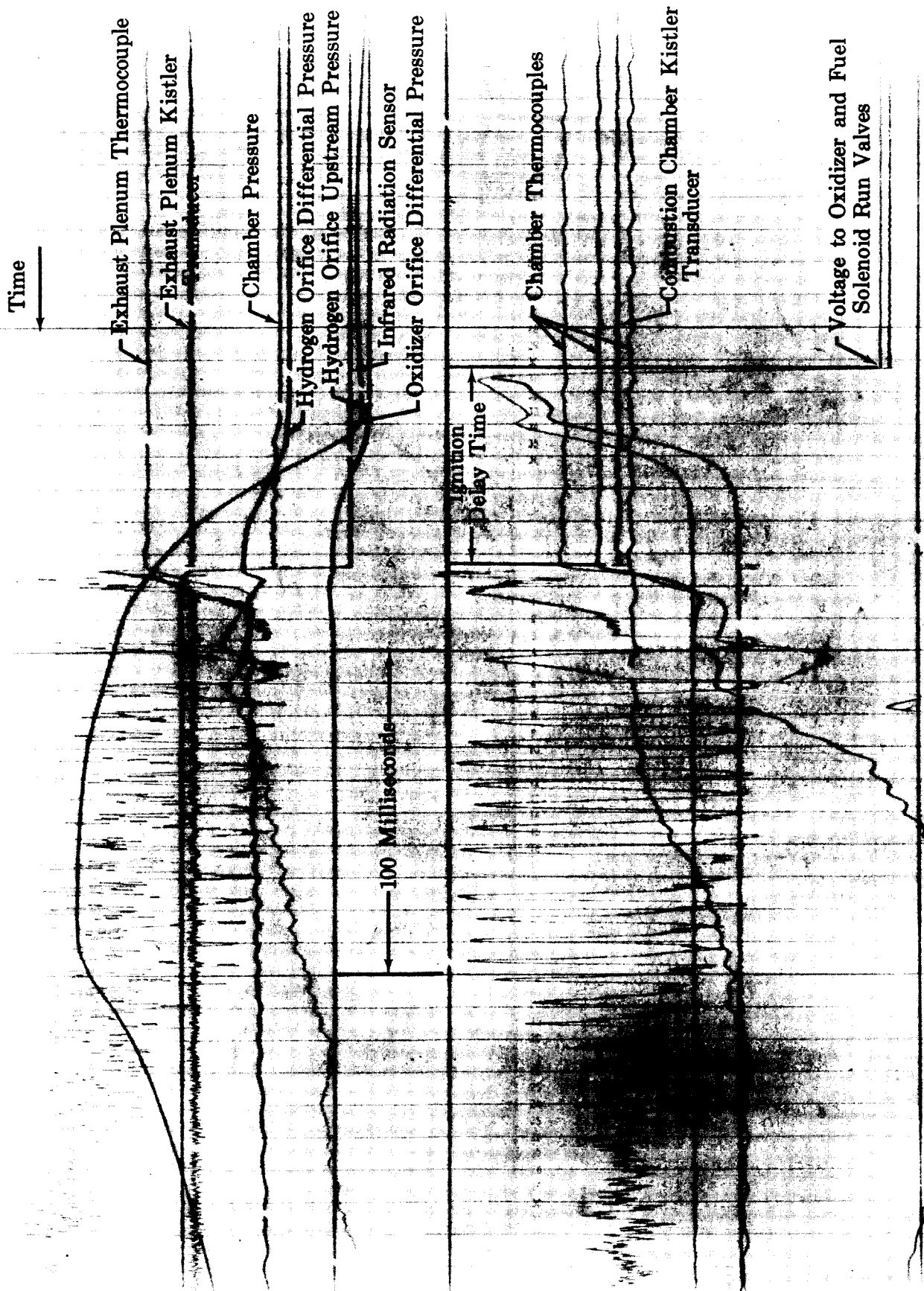


Figure 5. Oscillograph Trace of Ignition Occurring During Test No. 15.01

FD 19054

No ignition in either the chamber or the warm exhaust plenum was recorded for the third series of tests conducted with 39.5% fluorine in flox.

Ignition delay times for the fourth series of tests, using 50.2% fluorine in flox, ranged from 48.2 to 509 millisec. In the latter instance (test No. 32.01) ignition occurred in the warm exhaust plenum first, but combustion was not sustained. In all tests except test No. 32.01, there was approximately a 0.25 millisec lag in ignition response between the Kistler transducer located in the combustion chamber and the one located in the exhaust plenum. In test No. 32.01, the exhaust plenum Kistler transducer indicated ignition approximately 1.3 millisec sooner than the chamber Kistler transducer.

In the first test of the fifth series of tests, conducted with 46.5% fluorine in flox, combustion again was not sustained after a 265-millisec delayed ignition. Approximately 200 millisec later a fluorine reaction started in the oxidizer solenoid run valve, which damaged the test apparatus and precluded further testing. The damaged solenoid valve is shown in figure 6. The reaction is believed to have resulted when flox reached epoxy-filled windings through a failed internal weld between a thin-wall nonmagnetic sleeve and one of the magnetic ends of the solenoid valve.

The effects of mixture ratio, momentum ratio, and equivalence ratio* on ignition delay time for all tests in which ignition occurred are shown in figures 7, 8, and 9, respectively. At the lower mixture ratios there was an increased probability that combustion would not be sustained after ignition had occurred. There was an overall indication of a decrease in ignition delay time at higher mixture ratios. Most of the tests conducted at mixture ratios of approximately 5 and 8 had ignition delay times of less than 100 millisec, whereas a high percentage of the tests conducted at a mixture ratio of approximately 1 had ignition delay times greater than 100 millisec. The effect of mixture ratio is inversely reflected in momentum ratio and equivalence ratio because these parameters are inverse functions of mixture ratio.

*Stoichiometric mixture ratio/actual mixture ratio

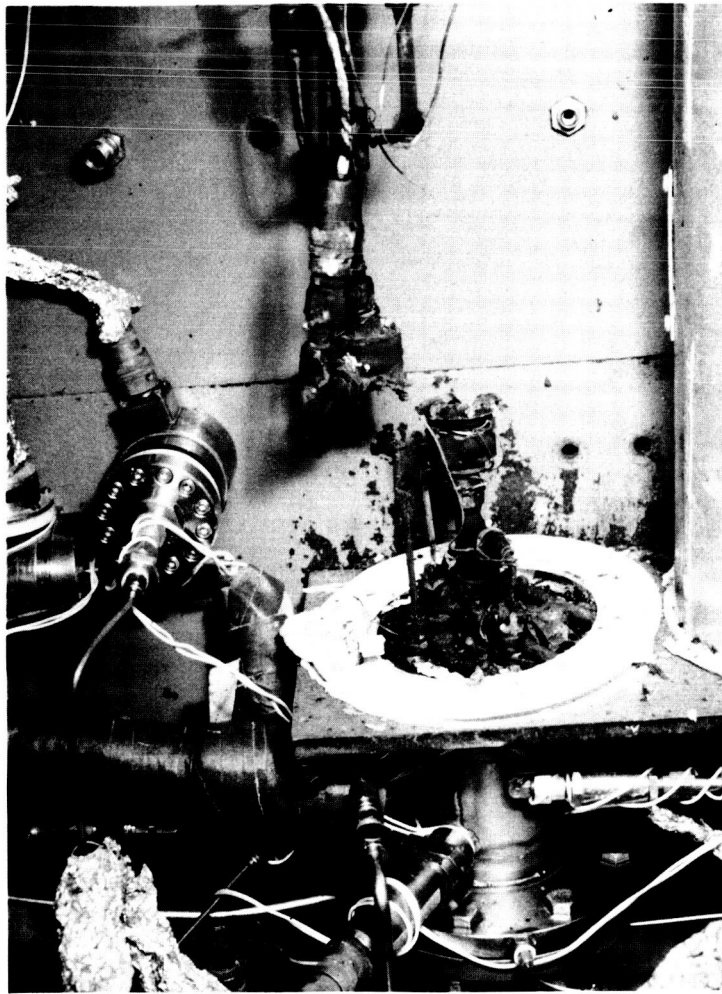


Figure 6. Oxidizer Solenoid Valve Showing
Fluorine Damage

FE 60996

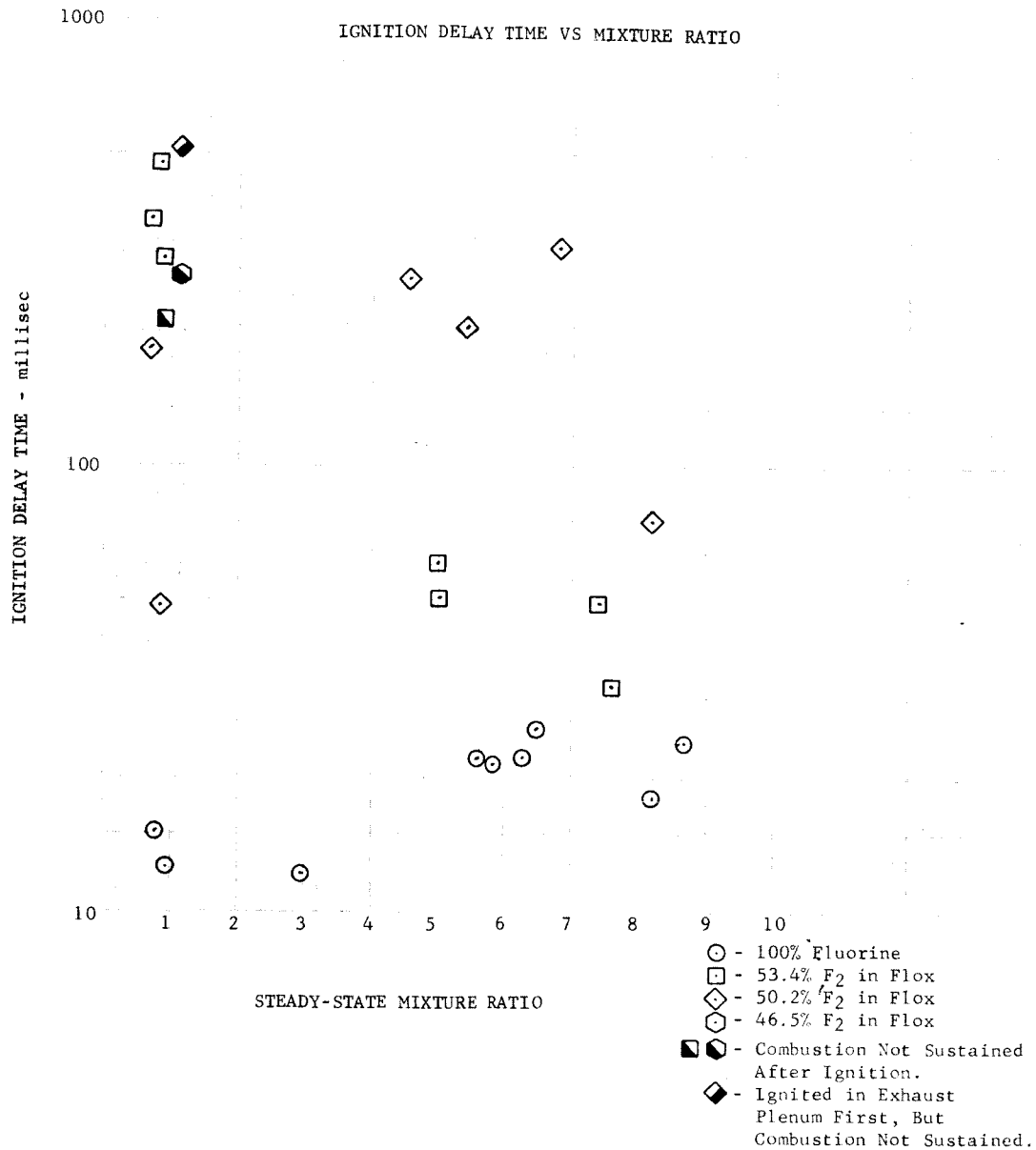


Figure 7. Effect of Mixture Ratio on Ignition Delay Time

DF 52589

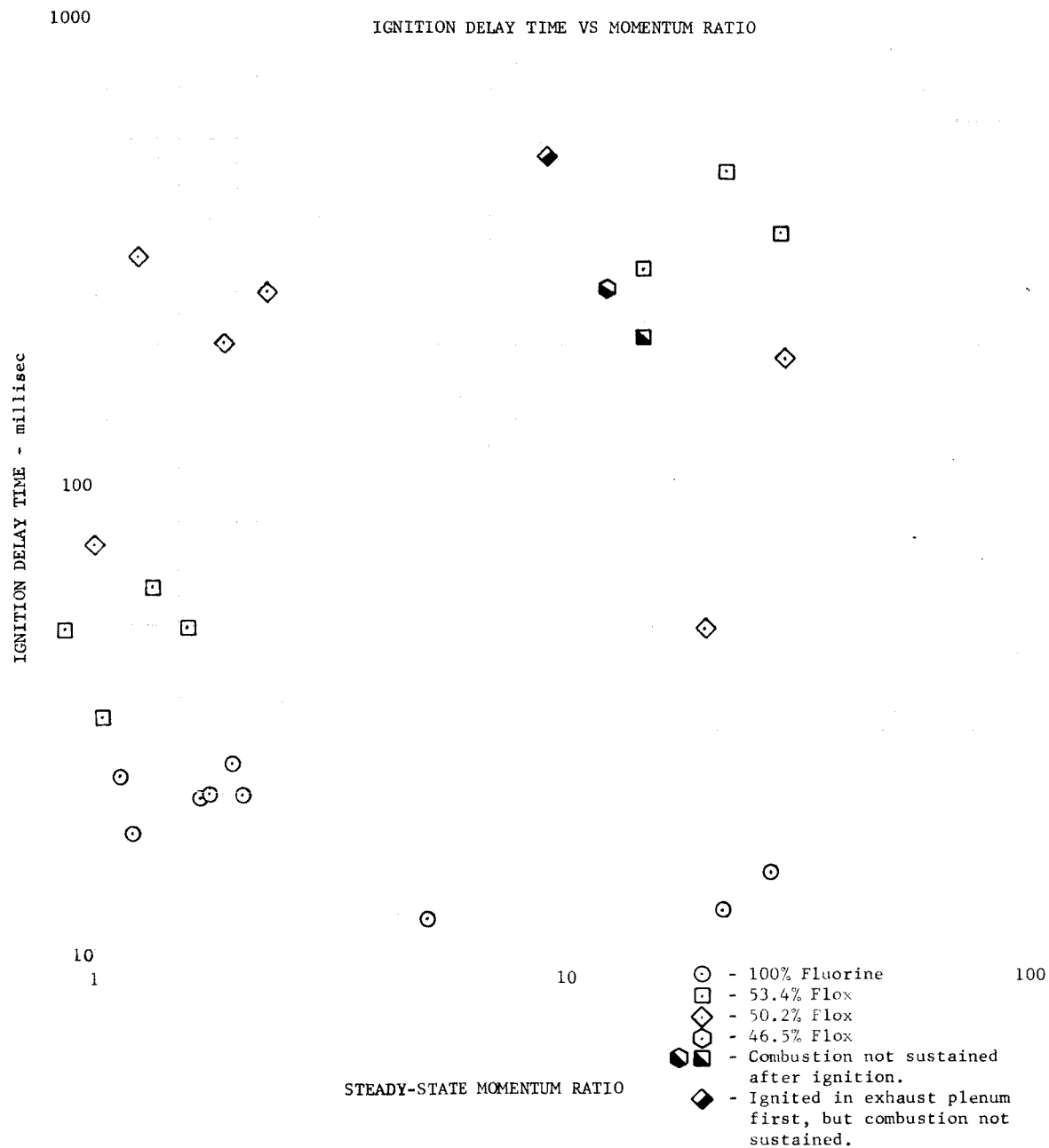


Figure 8. Effect of Momentum Ratio on Ignition Delay Time

DF 52590

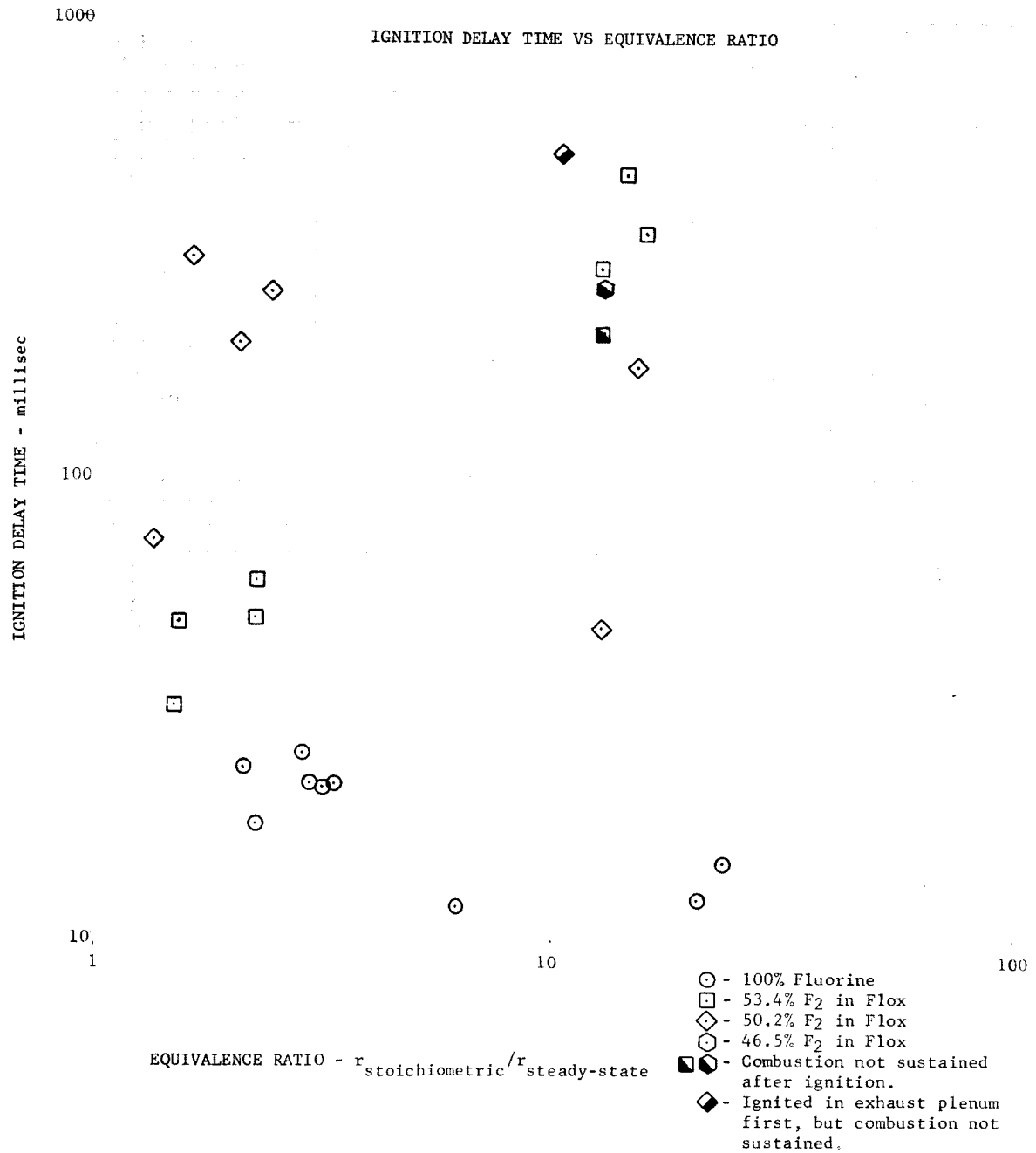


Figure 9. Effect of Equivalence Ratio on Ignition Delay Time DF 52591

SECTION V
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2. Mosier, S. A., R. E. Dotson, and O. K. Moehrbach, "Hypergolic Ignition of Light Hydrocarbon Fuels With Fluorine-Oxygen (Flox) Mixtures," WSCI 65-23, The Combustion Institute, October 1965.

APPENDIX A
TEST FACILITY

1. FACILITY DESCRIPTION

The flox/hydrogen hypergolicity program was accomplished on B-7 test stand in the Rocket Engine Component Test Area at Pratt & Whitney Aircraft's Florida Research and Development Center. An overall view of the test stand and its control room is shown in figure A-1. The test stand is equipped with specially designed fluorine-compatible oxidizer controls such as remote operating valves, check valves, and hand-operated valves. The capability exists for conducting a variety of ignition, combustion and chamber cooling investigations, and it is regularly used for such.

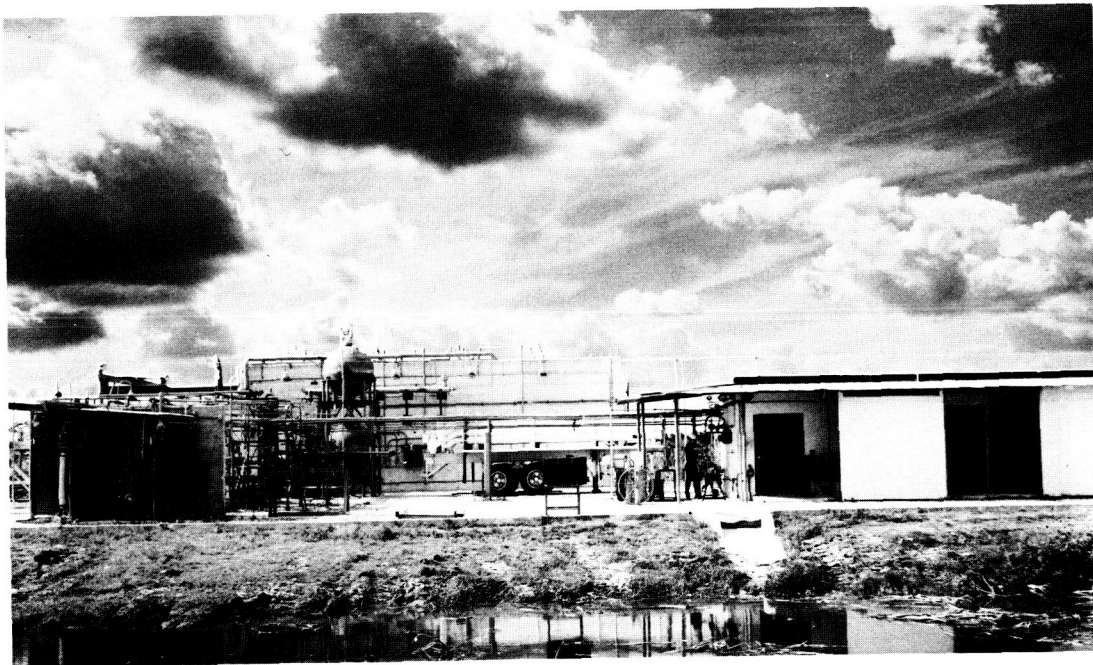


Figure A-1. Stand Complex and Control Room

FE 58475

Both oxygen and fluorine are supplied from standard gas storage bottles, which are kept in blast-protected storage racks. The oxygen supply pressure is 2200 psi and the fluorine supply pressure is 400 psi. Gaseous hydrogen is supplied from an 1800-psi test area distribution network.

The ancillary fluids available for use as purges include gaseous nitrogen from an 1800-psi test area distribution network and gaseous helium from 2200-psi standard gas storage bottles. All purge supply systems are equipped with driers to maintain the moisture content below 2 ppm. Liquid nitrogen is available to cool both the fuel and oxidizer to 140°R and can be supplied to the test stand in 3600-gal roadable dewars.

The control room features a 40-channel digital sequencer system, which is programable in 1-millisecond increments. The digital sequencer and its logic modules are shown in figure A-2. Any or all of the 40 channels can be timed "on" or "off" during the time interval of ± 999.999 seconds. A patchboard-type programmer is used to select the timing of each channel as well as to preset the sequencer to an initial starting time. In addition to start, stop, and presetting to the initial start time, the sequencer is also capable of skipping time or "advancing to shutdown."



Figure A-2. Digital Sequencer and Logic Modules

FC 12367

2. DATA ACQUISITION

A high-speed digital magnetic tape recording system shown in figure A-3 is available for use on B-7 test stand. It is capable of recording 60 low-level input analog to digital channels at a rate of 5000 samples per second with an accuracy of $\pm 0.2\%$ of full scale. The digital data are reduced to engineering units and processed into performance parameters directly from the tape record, using the IBM 360 computer in the Computing Laboratory. In conjunction with the digital tape recording system, simultaneous analog recording on a high-speed 36-channel oscillograph is possible. A 100-channel events recorder and 20 strip chart channels are available for pretest setup and for monitoring selected parameters during test.

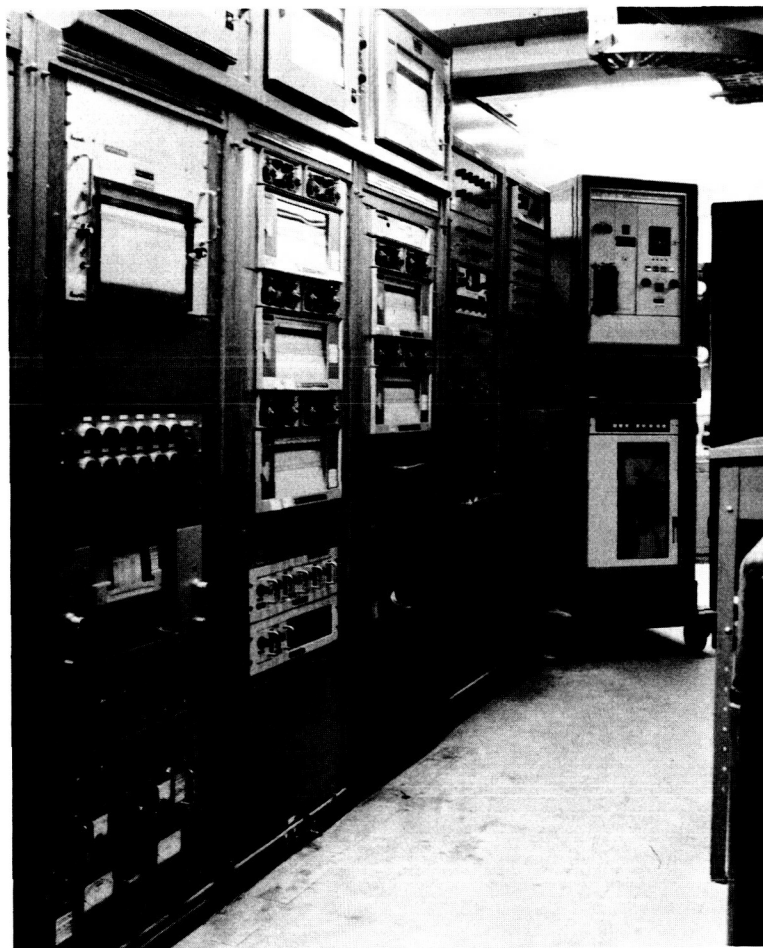


Figure A-3. High-Speed Digital Tape
Recording System

FC 12355

To ensure that accuracy remains within $\pm 0.3\%$ to 0.5% of full scale, all strain gage pressure transducers are calibrated at a minimum of 4-month intervals by comparing them to working standards maintained in the Instrumentation Laboratory. These working standards are compared with a Company-maintained primary standard that has been calibrated at the National Bureau of Standards. The Instrumentation Engineering Group maintains a computerized record of all evaluations, calibrations, and maintenance relating to all sensing and recording instrumentation. The Data Validity Group reviews all data to ensure that accuracy limits are maintained.

3. FLUORINE PASSIVATION STAND

Passivation is the final step in the cleaning process of all parts destined for use in fluorine service. Passivation consists of exposure of the part to gaseous fluorine at ambient temperature with sequentially increased pressure stages to a final hard passivation period of 2 hours at 200 psi. This process permits any residual contaminants to react slowly without ignition and renders the part inert to liquid fluorine. All parts intended for liquid fluorine service are passivated in the Company-owned facility shown in figure A-4. Containers and equipment are available for the passivation of subassembly details and for the passivation of assemblies such as valves, pumps, injectors, and small chambers.

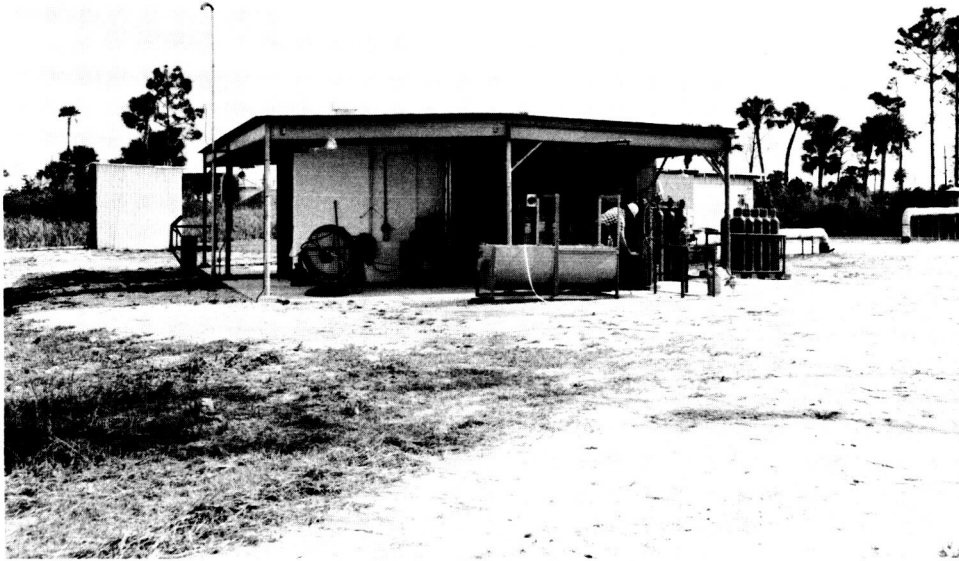


Figure A-4. Facility for Passivation of Liquid
Fluorine Parts

FC 9131